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ACCELERATOR DESIGN FOR THE HIGH-POWER INDUSTRIAL FEL*

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Abstract

We have developed a conceptual design for an industrial-use kilowatt UV and IR FEL driven by a recirculating, energy-recovering 200 MeV, 1-5 mA superconducting rf (SRF) electron accelerator. In this paper we describe the accelerator design of this FEL. The accelerator consists of a 10 MeV injector, a 96 MeV SRF linac with a two-pass transport which accelerates the beam to 200 MeV, followed by energy-recovery deceleration through two passes to the dump. Technical challenges include high-intensity injector development, multi-pass energy-recovery operation, SRF modifications and control for FEL operation, development of tuneable, nearly-isochronous, large-acceptance transports, and matching of the beam to the FEL wiggler. An overview of the accelerator design is presented.

I. INTRODUCTION

The CEBAF industrial FEL is planned as a prototype and test bed for future high-power, high-efficiency, industrial-use FELs. The purpose of the program is to develop the technology for producing high-power FEL light and to demonstrate the possible uses of FEL light over a broad range of possible applications.[1,2] Applications require tuneable light from the infrared (~20mm) to the ultraviolet (~160nm), at multi-kW power levels. This implies tuneable beam energies up to ~200 MeV, with beam powers of ~1 MW, and peak currents of ~200 A. Practical applications will require cost-effectiveness and energy-efficiency.[3] Therefore, we incorporate multi-pass acceleration and energy-recovery deceleration, and will use our experience in this prototype to develop a cost/reliability optimum. The accelerator must maintain small emittance (ε_N< 11 mm-mrad) in the acceleration to the wiggler, and have high acceptance (low losses) throughout.

II. ACCELERATOR DESCRIPTION

Table 1 summarizes the requirements of the FEL driver accelerator. For these requirements we have designed the accelerator system shown in Figure 1, and it consists of a 10 MeV photocathode-based injector, a 96 MV CEBAF-style SRF linac, with a two-pass recirculation transport. The system accelerates the beam from the injector through two passes of the linac to 200 MeV. The beam is compressed and matched into the FEL wiggler where it loses energy and greatly increases its energy spread, while producing coherent light. The resulting beam is decompressed, returned into the linac, decelerated for energy recovery through two passes to ~10 MeV, and then transferred into the dump. The two-pass design is the minimum needed to demonstrate both recirculation and energy-recovery. (More passes would add unwelcome complexity without reducing costs.) In the following sections we describe the accelerator components, and highlight significant features within the design.

Table 1 - FEL Accelerator Parameters

Electron Energy	E	100—200 MeV	
Accelerator type	two-pass SRF recirculator, with two-pass E-recovery		
RF frequency	$f=\omega/2\pi$	1.4997	GHz
Charge/bunch	Q	135	pC
* Transverse emittance	ε_N	11	mm-mrad
Longitudinal emittance	ε_L	60	π keV-ps
Rep. rate (start-up)		2.339	MHz
Rep. rate (production)		37.425	MHz
Total Current	I	5	mA
UV/IR wiggler focus	β	1/2.5	m
rms energy spread	$\Delta E/E$	0.15	%
rms bunch length	$\Delta\phi_{rms}$	0.2	ps

A. Injector

The injector must provide high-intensity (large space-charge) bunches, with high beam quality, at 5 mA cw operation. Our design consists of a 500 kV DC laser-driven photocathode gun, a room-temperature 500 kV, 500 MHz buncher, a CEBAF-style quarter-cryomodule providing 10 MV of SRF acceleration, and a transport line matching into the main driver at 10 MeV for acceleration in the linac.[4] Our high-intensity source is designed to deliver 35 ps electron pulses with charges of up to 200 pC. The beam is bunched and accelerated by the buncher and SRF, and then transported into the linac by a 4-quad "zoom-lens" and an achromatic dipole triplet, which permits variable matching. Design calculations show that the injector can produce ~1.5 ps bunches of 135 pC at ε_N < 6 mm-mrad, within FEL specs. A significant R&D challenge is to obtain long photocathode lifetimes at the design current, with high beam quality, while handling large space-charge effects. This design will be verified by CEBAF Injector Test Stand [4] experience.

B. Linac

The linac consists of three modified CEBAF cryomodules, with magnetic focussing elements between the cryomodules. Each cryomodule contains eight 5-cell 1500-MHz CEBAF cavities with fundamental power couplers, HOM couplers,

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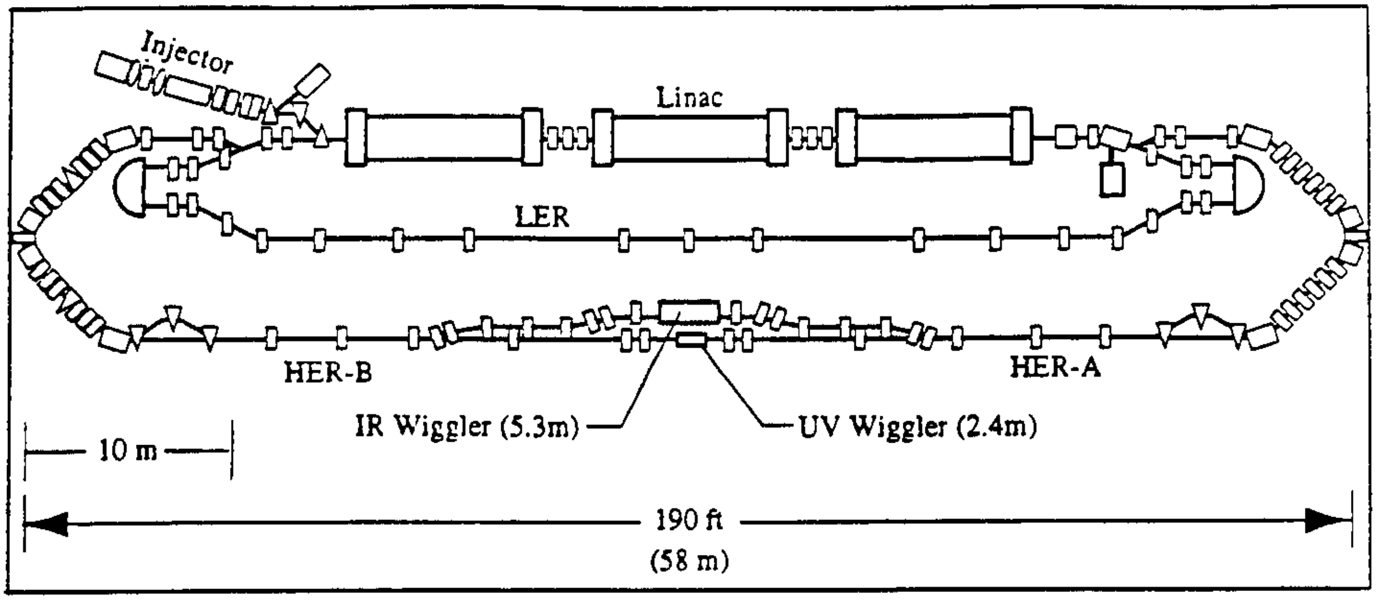

Figure 1. Overview of FEL Driver Accelerator, showing 10 MeV injector, 96 MV linac, low-energy recirculation transport (LER) for 105 MeV beam, and high-energy recirculation transport (HER-A) which takes 200 MeV beam to the UV or IR FEL wiggler and returns it to the Linac for energy recovery (HER-B).

intercavity steps, and cryogenic components. CEBAF experience indicates that each cryomodule should be able to provide at least 32 MV of acceleration. These cryomodules are modified to accommodate the high-peak- current, low-loss FEL operation. HOM load power is dissipated at 50K to reduce thermal loads. The intercavity apertures are enlarged, bellows and ports are shielded, and steps are minimized to reduce impedances. The Linac includes quad triplets and skew-quads between the cryomodules, and a quad doublet after the last cryomodule for multi-pass focusing and matching.

C. Recirculation transport

The recirculation beam transport contains two lines. The low-energy recirculation (LER) transport takes ~105 MeV beam from the exit of the linac and returns it to the entrance in both acceleration and deceleration cycles. The LER is similar to the Bates recirculator [5], and consists of arcs with a 180° bend and two normal and reverse 20° bends which are arranged to obtain isochronous and achromatic motion. The straight section contains three quad triplets, with the overall x-y transport fitted to a -I matrix. The beam is "on-crest" in the first and last linac passes to minimize the momentum width within the LER to < ±1%, which maximizes acceptance.

The high-energy recirculation (HER) transport is the outer loop of Figure 1. The HER carries the beam around the high-energy arc from the linac to the wiggler and returns it for energy recovery. The beam is accelerated "off-crest" on the second linac pass and the HER is non-isochronous to enable bunching and debunching. The HER must accept a large energy spread, particularly in the beam exiting the wiggler, and have broad tuneability in transverse and longitudinal focusing. The present design shown in Figure 1 meets these requirements. The arcs are based on a two-cell reverse bend configuration,[6] in which a small negative bend at large dispersion combines with a large bend at small dispersion to provide nearly isochronous motion. The arc quads can be varied to change the chronicity M_{56} by ±0.05 by minor retunings, and to obtain M_{56} = 0 ± 0.30 with larger changes. The transport includes beam-separation chicanes and path-length adjustment chicanes as well as matching transport into both UV and IR wigglers.

The IR FEL requires a separate wiggler from the UV FEL, which is placed in a bypass parallel to the UV FEL. This bypass is an achromatic staircase (see Fig. 1). For longer-wavelength operation, 100 MeV beam is sufficient and it is desirable to have a long, small ΔE/E bunch. This can be obtained in a single on-crest pass of the linac, with dipoles tuned to steer the ~ 100 MeV beam into the HER and into the IR wiggler. Single-pass (off-crest) debunching and energy-recovery follow. This single-pass operation is simpler and has less stringent aperture and stability requirements.

D. Transport to Dump

Following two-pass deceleration the ~10 MeV beam is separated into the dump transport. The separation is obtained in a split dipole at the end of the linac, with the first half extracting the low-energy beam from 105 and 200 MeV beams, and the second half tuned to optimize the 105/200 MeV beam separation. The extracted low-energy beam is transported into a 10 MeV, 50 kW dump. The split dipole makes it possible to tune the transports to vary the matched beam energies through the system, and enables ~100 MeV single-pass operation.

III. LONGITUDINAL MOTION

The longitudinal motion is critical in the driver design. Conceptually, we take a relatively long, low-energy-spread bunch from the injector and transform it into a short, increased-energy-spread bunch at the wiggler, obtaining high-peak current. At the wiggler, the beam loses energy and greatly increases its energy spread in the FEL interaction. To transport the beam to the dump we must decrease this energy spread, and therefore we must debunch this short, large-energy-spread beam into a long, moderate-energy-spread bunch within the acceptance of the machine.[7] Each of these processes requires rotating the beam in longitudinal phase space.

In our design, the rotations are obtained in a simplest way. The first-pass acceleration to 105 MeV is on-crest and isochronous. The second-pass acceleration to 200 MeV is off-crest, and places a position-dependent energy tilt on the beam ($\Delta E(z) = -eV_{rf} \sin(\phi_2) k\, z$, where V_{rf}, ϕ_2 are the rf voltage and phase, respectively, and $k = 2\pi/\lambda$). The HER transport to the wiggler is slightly non-isochronous and changes particle positions ($\Delta z(\Delta E) = M_{56} \Delta E/E$), resulting in a bunching phase-space rotation, if $k\, M_{56} eV_{rf} \sin(\phi_2)/E \approx 1$. Bunching by up to an order of magnitude is obtained.

Following the wiggler, the process is reversed, with a non-isochronous return transport followed by off-crest deceleration to 105 MeV in the third Linac pass, and on-crest deceleration through a fourth Linac pass to 10 MeV, where the spent beam is extracted and deposited the dump.

This scenario requires matched M_{56} throughout the lattice and a large ΔE acceptance, particularly for the beam exiting the wiggler in the HER, where $\Delta E \sim \pm 5$ MeV. Energy width acceptances of $\Delta E \sim \pm 1$ MeV are required in the remainder of the machine. The longitudinal motion is also complicated by nonlinearities due to the *rf* waveform, the beam transport, and wakefields. These effects are incorporated into the complete design [2].

IV. ACCEPTANCE AND STABILITY ANALYSES

Particle tracking codes (DIMAD, TLIE, PARMELA) have been used to determine the acceptance and explore the nonlinear and chromatic motion in the lattice. The simulations show that adequate acceptance is obtained throughout the system, with, in particular, linear motion over a large acceptance in the HER transport, and acceptance through the final linac pass into the dump.

The apertures throughout the accelerator have been chosen to enable low losses. Typically, apertures greater than 6σ are allotted, with allowance for energy acceptance and closed-orbit/misalignment errors. Also, the impedance of the accelerator has been minimized to enable high-peak current by removing steps, shielding bellows, using low-impedance beam position monitors, etc. An impedance budget of less than 1 kV/pC per pass has been set.

The FEL accelerator operation is complicated by energy recovery, which must be maintained with the perturbations of FEL operation. With energy recovery, the external energy that must be supplied to the cavities is greatly reduced, to ~1.5 kW/cavity. The relatively small amount of external power also implies a relatively weak degree of external control. Extensive modeling has demonstrated that the CEBAF rf control system can provide adequate control of the accelerating field with modest gains.[8]

Phase oscillations and beam loss can cause an unstable fluctuations in the accelerating field, particularly when coupled through the chronicity M_{56} to fluctuations in the beam phases.[9] A threshold current for this instability can be written as $I \sim E/(eR_s M_{56} k\, S)$, where R_s is the shunt impedance, M_{56} is the total HER chronicity and S is the sum of the sines of the phase differences between the up and down passes. At current design parameters, this threshold is ~0.2 mA. At our design goal of 5 mA, this means that active feedback is required to control the instability.

Alternatively, the lattice can be modified to have opposite signs of M_{56} for the lattice segments entering and leaving the wiggler (so that the total M_{56} is ~ 0), and the beam phases could be arranged to cancel. An operational mode with these properties has been developed.[2] However, it would require off-crest first pass acceleration, and a much larger LER energy aperture. The lattice can be adapted to accommodate either mode, and the optimum can be determined operationally.

Other instabilities and high-intensity effects have been considered. These include ion trapping, coherent curvature effects and synchrotron radiation, and multibunch beam break-up.[2] None of these presents serious difficulty.

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